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FLIGHT TELEROBOT MECHANISM DESIGN: PROBLEMS AND CHALLENGES

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ABSTRACT

This paper attempts to state some of the problems and challenges of designing flight telerobot mechanisms. Specific experiences are drawn from four different system developments at JPL, namely, the Force Reflecting Hand Controller, the Smart End Effector, the force-torque sensor, and a generic multi-degrees-of-freedom manipulator.

INTRODUCTION

An advanced telerobot system, which is the unification of teleoperation and robotics, is composed of many subsystems and assemblies. Some of these subsystems contain complex mechanisms, complete with sensors, electronics, and control processors. Many on-going research programs in the U.S. and internationally are directed toward the development of laboratory mechanisms and telerobot technology for terrestrial applications. Very few programs are addressing the development of flight telerobot mechanisms. In fact, the only flight manipulator now existing is the Space Shuttle Remote Manipulator System (RMS). Certainly, NASA's Flight Telerobot Servicer project [1,2] is the first major effort in developing a flight telerobot system in the U.S.

In parallel with and also in support of this Flight Telerobot Servicer project, the Jet Propulsion Laboratory (JPL) is developing a ground telerobot Demonstration System [3], which is a system-wide technology development, integration, and demonstration project. Because of the complexity of the total system, and in concert with the NASREM approach [4], the JPL Telerobot Demonstration System has a hierarchical architecture, as depicted in Figure 1.

The JPL architecture contains an Operator Control Station, a Reasoning and Planning Subsystem (also known as the Artificial Intelligence Planner), a Run-Time Control Subsystem, a Manipulator Control and Mechanization Subsystem, and a Sensing and Perception Subsystem. The Human Operator is not shown in this figure, but is implicit as the "commander" of the system, located at the Operator Control Station. Teleoperation elements are physically distributed

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among the Operator Control Station and the Manipulator Control and Mechanization Subsystem. Figure 1 also depicts the data flow in the two telerobot operational modes, namely teleoperation mode and supervised autonomous mode.

The telerobot mechanisms chosen for discussion in this paper are: (1) Force Reflecting Hand Controller (FRHC) - the input device used during teleoperation mode; (2) GSEE - the robot end effector used in both teleoperation and autonomous modes; (3) force-torque sensor - as part of the GSEE and as an individual sensor; and (4) a generic multi-DOF (degrees-of-freedom) manipulator - the telerobot output device. Specific experiences at JPL, resulting from ground telerobot system development and some flight system development, are summarized in this paper. Through this summary, the many challenges and design problems are exposed, which are common to future flight telerobot systems.

TELEROBOT MECHANISMS - COMPLEX INTEGRATED SYSTEMS

Flight telerobot mechanism design offers special problems and challenges. This is because of the relatively young state-of-the-art technology in telerobot mechanisms, let alone in flight telerobot systems.

Telerobot mechanisms are complex integrated systems. Because of the real-time processing requirements and normally immense data acquisition and dissemination, electronics are often distributed along and/or embedded within the mechanism. Distributed microprocessors are also often designed for optimum data processing and throughput, rather than centralized single-CPU processing. Thus, experience shows that mechanics, electronics, and controls are integrated design issues; hence, early top-down system design considerations are required.

Complex telerobot mechanisms are required in telerobot systems. A telerobot system is an extension of the human operator, designed so that even though the operator is remote from the worksite, the system provides all the necessary input and output devices/data/information to enable him to execute a task as if he were present at the task. This kind of proprioceptive and kinesthetic man-machine interface is said to provide "telepresence." One main attribute of telepresence is force sensing and feedback, which is particularly essential for the performance of dexterous task execution.

Indeed, a lot of research has been devoted to dexterous teleoperation and autonomous robotic operation with real-time sensory feedback and control. This paper addresses only a few elements in this area. The first subject of discussion, the FRHC, is an input device which is capable of force feedback, thus providing the operator with a kinesthetic sense of how the remote manipulator reacts to the environment and to the task object. The second subject of discussion, the GSEE, is a manipulator end effector which provides the capability of dexterous grasping of an object, and also provides sensing of the forces and torques experienced at the wrist of the manipulator. The third subject of discussion, the force-torque sensor, is the heart of this force feedback and control. The last subject of discussion, a generic manipulator, is the executor of all telerobotic actions. By covering these four subjects, a large class of telerobot mechanisms will be dissected and analyzed.

FRHC - HAND CONTROLLER MECHANISM SYSTEM

The JPL FRHC (Fig. 2) is a general non-master-slave 6-DOF input device capable of backdriving itself [5,6]. It is a ground-based system designed primarily for research purposes as an input device for teleoperating a manipulator arm. By contrast, other 6-DOF non-master-slave input devices such as the Canadian Aerospace Electronics (CAE) trackball and the MSFC controllers, have normally limited travel envelopes, but are not capable of force reflection. Some newer designs at Martin Marietta and at Japan's Ministry of International Trade and Industry (MITI) have force feedback features and comparable travel envelopes as in the JPL FRHC. A comprehensive survey and qualitative evaluation of hand controllers can be found in Reference 7.

This FRHC has 6 DOF, each joint containing its own encoder and dc motor drive. Used as an input device, it provides a 6-DOF cartesian (position and orientation) input to a remote manipulator arm having 6 or more DOFs. As a matter of fact, the FRHC can also be used as a stand-alone robot manipulator device, providing 6-DOF actuation. However, the FRHC is primarily designed as an input device, and therefore is a robot with limited capability.

Two FRHCs, one right-handed and the other left-handed, have been integrated into the JPL/NASA Telerobot Demonstration System, shown in Figure 7. Here, the operator uses the FRHCs to control two robots, grappling and working with a mock-up satellite [8].

JPL is in the process of designing a flight force reflecting hand controller to be flown as part of the Robotic Technology Experiment (ROTEX) experiment in D-2 Spacelab of Federal Republic of Germany (FRG), now planned for 1991 [9]. In that experiment, the JPL flight hand controller (and electronics) will be used as one of the input devices to control a space robot arm developed by FRG. Force reflecting experiments will be conducted and analyzed, deriving guidelines for future design of flight force reflecting teleoperation and telerobot systems.

The following discussion will attempt to summarize certain existing design features, and then list some desirable future design features.

Requirements

High Control Bandwidth - If a telerobot system is to have high control bandwidth, both in its position and in its force control loop, the subsystems and mechanisms, including this FRHC, need to have high frequency response. It is well known that in a mechanical system, its natural frequency is directly proportional to the square root of its stiffness, and inversely proportional to the square root of its inertia. Hence, the FRHC is desired to have high stiffness and low inertia.

Low Friction - Friction in the FRHC will distort the kinesthetic feedback to the operator, whether the FRHC is used to move the manipulator in free space or when the manipulator is in contact with a task object. The problem is compounded if the friction is not constant in the FRHC work envelope.

Low Effective Inertia - The FRHC needs to be designed so that the dynamics of the hand controller do not compromise the operator's kinesthetic sense of the manipulator motion.

Uniform Isotropic Effective Inertia - Uniform inertia in all directions is desired so as to minimize inertia's effects on operator motion. Experience has shown that if the FRHC has non-isotropic inertia, the FRHC will tend to move in the direction of the least inertia when the operator applies a force (motion) to it.

Design Options

As might be expected, some of the above requirements are conflicting. In the design of the FRHC, there are four major groups into which design options can be categorized:

Kinematics - The FRHC is required to input to the manipulator a 6-DOF position (3 translations and 3 rotations) with 6-DOF force/torque feedback. It is supposed to be a universal non-master-slave input device, i.e., it is not required to have the same link configuration as the remote manipulator. Thus, a multitude of FRHC joint configurations could be designed as in the case of manipulator arm designs. Link configuration could be cartesian, spherical, or articulated.

Structure - This is the main design factor affecting the natural frequency of the hand controller. The present FRHC design employs thin wall tubings as the main link members, in order to achieve high stiffness and low mass. Preloaded bearings are used to maximize joint stiffness, while compromising on friction.

Transmission - Transmission design affects joint stiffness, friction, mechanical advantage, efficiency, extent of backlash, and the placement of actuators. To date, the hand controllers developed at JPL, including this FRHC, all employ pre-tensioned cable/pulley transmissions for the reasons of high stiffness, low weight, low friction, zero backlash, minimal torque variation, and the ability to place the actuators away from the joints.

Actuators - From among the selections of pneumatic, hydraulic, and electric actuators, the FRHC was designed with conventional dc motors. Ripple torque effects, cogging torque effects, and brush frictions are the disadvantages of such a choice. With brushless dc motors, friction effects are minimized; however, electronics design becomes a bit more complex.

Future Design Considerations and Challenges

To date, the best FRHC system bandwidth achieved is estimated to be approximately 10 Hz. A prime objective of future work is to significantly improve this system characteristic. A bandwidth of 25 to 30 Hz is the goal of the flight FRHC presently under development for the ROTEX experiment [9].

Alternative FRHC designs need to be examined and comparatively evaluated. While the existing FRHC has a spherical coordinate design, two new designs are now being evaluated: a cartesian hand controller and an articulated (anthropomorphic) hand controller. Also, alternative designs in the transmission need to be examined. Their effects on stiffness and friction on the overall performance need to be investigated.

GSEE - SMART END EFFECTOR

The GSEE is a set of two smart end effectors developed at JPL for Goddard Space Flight Center. This GSEE [10] is designed to interface with the PUMA 762 robot arm. Its system design evolved from two earlier JPL smart end effector developments [11,12], one designed for the Orbital Maneuvering Vehicle and tested at Marshall Space Flight Center, and the second designed for the PUMA 560 robot at JPL.

Other development efforts in sensory control robot grippers are on-going in the industry (e.g., the Lord gripper and the Telerobotic Research Inc. gripper) and research centers. Much attention in recent years has also been given to multi-fingered hands. Notable for their brilliant but very complex designs, both in mechanism and in controls design, are the Salisbury (MIT/JPL) 3-finger hand the Jacobson (Utah) 4-finger hand. A thorough discussion on robot hands can be found in Reference 13. The GSEE is discussed here because its design is based on expected space applications.

The GSEE (Fig. 3) has all its electronics, microprocessor, and two sets of robotic sensors integrated at the end effector, thus minimizing the external interface to a RS-232 serial line for data, plus a power line. The two sets of sensors are a 6-DOF force-torque sensor and a set of two grip-force sensors. The former is familiarly known as the wrist force sensor, and the latter measures the grip force at the base of the fingers of the GSEE. Local electronics perform the conditioning of the data, analog-to-digital conversion, and multiplexing of the data. In addition, a communication process in the local processor performs the packaging and depackaging of the data, which is shipped over the RS-232 serial data line. Force-torque data and other engineering data is shipped to the external world, while commands and status requests are received by the GSEE. The local microprocessor performs the control computations for the closing, opening, and force control of the GSEE gripper; the control loop is closed at around 100 Hz.

Requirements

High Stiffness - The end effector must work in an end-to-end manipulator system, and in a tool and task environment where flexibility and compliance might be distributed, thus requiring active compliant advanced controls. In order not to add another complication to the control design, this end effector must have higher stiffness and mechanical bandwidth than the overall system.

Low Mass and Inertia - This requirement is necessary to minimize the dynamic effects on the control of the manipulator. For laboratory systems where payloads of the manipulator may be limited, extra mass and inertia from the end effector may degrade manipulator performance.

Force Control - For dexterous control during task execution, it is desirable to have control of the grasping force of the end effector. Current research is investigating compliant grasping with self-centering of fingers.

Design Options

Kinematics - Even with simple grippers, a number of kinematic arrangements is possible. The most popular design is the parallel jaw gripper which has low complexity, high grasp force to weight ratio, and ease of control. The GSEE utilizes a design in which both jaws are translated directly toward each other. The motion of grippers is linear, unlike a 4-bar linkage gripper that effectively has x-y motion when the gripper is closed or opened.

Structure - Design of the structure must be stiff but light, considering adequate thermal pathway or heatsink from the local electronics, especially the motor. Particularly during active clamping on an object, the motor will generate excessive heat and will cause failures if the heat is not properly dissipated. The heat sink design is critical for flight systems, which operate in the absence of an atmosphere.

Transmission - The transmission system selected depends heavily on the kinematics design. The transmission should have light weight, high stiffness, low friction, and should demonstrate little or no backlash. Low friction and little backlash are necessary for good position and force control. Past designs at JPL have used ball screws and rack-and-pinion drives for jaw actuation, using multi-stage gear reductions between the motor and the fingers.

Actuators - Direct current (dc) servomotors are most commonly used for grippers employing force control. To minimize heat generation, motors with high torque constants and low winding resistance are used. Torque output per unit mass should be high and motor friction should be low.

Future Design Considerations and Challenges

Performance of existing designs can be improved by further reducing friction levels present in the drive and actuation mechanisms. Placement of different sensors and real-time integration of the sensor information into local control loops will bring about more dexterous end effectors.

New end-effector finger design will expand the capability of the parallel jaw grippers. Self-centering fingers with quick release (quick change) mechanisms will further enhance the capability. Also, drastically different designs such as multi-DOF hands or multi-finger hands should be considered.

FORCE-TORQUE SENSOR

Since 1978, JPL has been developing wrist force-torque sensors that measure 6-DOF forces and torques. These sensors have been developed separately as well as being integrated with grippers for the performance of dexterous teleoperation. Experimental results using force-torque sensing for robot arm tele-manipulation, using the ground Shuttle RMS arm replica at Johnson Space Center and the ground OMV arm at MSFC have been reported [14,15].

A flight version of the same design has been under development for a planned Shuttle flight experiment in 1990. Figure 5 shows this flight sensor as compared to the ground sensor, Figure 4, which was developed for earlier feasibility experiments at JSC. Figure 6 is a schematic diagram for both sensors. Both sensors have the same goal specifications in terms of the range in payload force-torque sensing. The range is 880 N (200 lb) in forces and 270 N-m (200 ft-lb) in torques.

Casual comparison of Figures 4 and 5 reveals design differences between the two sensors, even though they are designed to the same operational force and torque range. In the following paragraphs, pertinent design changes necessary to move closer to a space-qualified sensor are discussed.

System and Flight Related Specifications

The flight sensor carries the following specifications:

- Launch dynamic g-loading in the Shuttle
- Launch configuration which has this sensor mounted at the end of the Shuttle RMS robot arm, with the Special Purpose End Effector (SPEE) mounted at the other end of the sensor; SPEE is the standard end effector of the Shuttle RMS arm.
- Flight safety considerations
- Flight electronics to be located in the Shuttle mid-aft-deck

- Power to in-situ (at sensor) electronics and data line limited to existing cable routed along the Shuttle RMS arm.

Because of the above specifications, major design changes had to be made to the ground sensor. The most major design change is due to the launch configuration and g-loading.

The flight sensor is now designed to the following specifications, as compared to goal specifications of 270 N-m (200 ft-lb) and 880 N (200 lb), with sensitivity at 0.27 N-m (0.2 ft-lb) and 0.88 N (0.2 lb):

		Operational Performance Parameters	
	Launch Design Load	Range	Sensitivity
M_x	610 N-m (450 ft-lb)	680 N-m (500 ft-lb)	0.49 N-m (0.36 ft-lb)
M_y	2,400 N-m (1,760 ft-lb)	857 N-m (630 ft-lb)	0.86 N-m (0.62 ft-lb)
M_z	2,400 N-m (1.760 ft-lb)	857 N-m (630 ft-lb)	0.86 N-m (0.62 ft-lb)
F_x	47,100 N (10,560 lb)	16,700 N (3,764 lb)	16.5 N (3.7 lb)
F_y	7,250 N (1,625 lb)	3,980 N (892 lb)	4.0 N (0.9 lb)
F_z	7,250 N (1,625 lb)	3,980 N (892 lb)	4.0 N (0.9 lb)

where M_x, M_y, and M_z denote the x, y, and z torques, and F_x, F_y, and F_z denote the x, y, and z forces. Notice the sacrifice in the sensitivity of the operational ranges, because of the large range of forces and torques the sensor is now measuring.

Another noticeable difference in the flight sensor design is the need for temperature gradient compensation and absolute temperature compensation, because of the Shuttle space environment. Safety concerns also led to a number of actions: strength of the overload pin was increased; careful structural and fracture mechanics analyses were performed; finite-element model analyses were made to study the structural frequencies; and special placement of the strain gauges was designed, with selection of space qualified gauges and bonding compounds of the gauges.

In support of the calibration of the sensor, whose dynamic range was significantly increased over the ground sensor design, a special heavy duty calibration jig sitting on a stable base (like an optical bench) had to be developed. Previous crude methods of hanging weights to calibrate the ground version of 270 N-m/880 N (200 ft-lb/200 lb) sensor obviously would not work. On this jig, strain gauges were also instrumented, and these gauges in turn had to be calibrated.

System design also called for an analysis of the loading on the Shuttle RMS arm when loads up to the maximum range of the sensor are actually applied to the RMS.

A GENERIC MULTI-DOF MANIPULATOR

As mentioned in the Introduction, there is only one existing flight manipulator arm, namely the Space Shuttle RMS. The RMS has capabilities designed for large excursions and transports of large payloads (in space). Its requirements are far from being compatible with telerobot requirements where accurate, robust, and versatile motion of the manipulator is required. Control systems for dexterous manipulation also call for position-force control using rigid arms; such properties are absent in the RMS.

JPL has not developed a flight telerobot manipulator arm; its closest development is the flight FRHC (see earlier section of paper), which can be considered a flight manipulator. However, based on the experience with industrial robot arms, the latest research arms from Robot Research Inc., and the Laboratory Telerobot Manipulator (LTM) from Langley Research Center/Oakridge National Laboratory, certain observations can be drawn. They are provided in the following paragraphs.

Existing methods of specification for industrial robot arms are inadequate and likely unsuitable for specifying flight telerobot arms. Real-time processing and advanced controls using position-force control and adaptive control create heavy demands on dedicated processing and data communication that may be incompatible with current space station designs (of other platform). In consideration of the whole system, dynamic interaction of the robot arm with the robot task will create disturbance to the space station that may be outside its acceptable range.

The following lists present desirable features to be included or considered by the mechanism designer in the specification and design of future flight telerobot arms. This list is based on experience with certain industrial and experimental robot arms, exposure to system studies for the design of a flight telerobot system, and on the current design of the JPL ground Telerobot Demonstration System.

<u>System and Flight Related Specifications</u>

- Robot configuration and degrees of (redundant) freedom
- Robot speed, within the range of safety of flight operation and degree of dynamic interaction with the vehicle, where the robot arm is housed
- Robot effective inertia, with due consideration of payload augmented inertia; compatibility with flight system attitude control
- Dexterity required of robot arm manipulation versus size of robot
- Absolute accuracy, resolution, and calibration methodology; in consideration of the tasks required of the robot

- Data throughput from robot to supporting electronics/subsystems; compatibility with flight system data distribution design.

Mechanical, Electrical and Data Communication

- Structural flexibility versus desired dexterity of robot
- Direct drive, geared drive versus other power transmission schemes
- Trading between routing of many cables with distributed local electronics and intelligence
- Electrical data line versus optical fiber data line
- Data throughput rate
- Distributed processors (physical distribution) versus localized processing (which may still use distributed processors - distributed in data processing, not physical distribution).

Control and Real Time Processing

- Advanced control requires data cycle rates greater than 100 Hz; robotic computation requires a 10 MIPS machine
- Flexible robot arm control requires new concepts of sensors and control algorithms
- Flight system attitude compensation needs to be designed in coordination with robot arm control laws
- Position-force control of robot arms needs to be designed in coordination with flexible robot arm control.

User Interface

- For payload specialists to operate robot arms, simple robot arm macro commands are desired
- For telerobotic control where the operator interacts continuously with the robot arm and other controls, effective and efficient operator interface are desired.

CONCLUSIONS

Designing flight telerobot mechanisms requires a heritage and library of design rules that are only partially available. This paper has attempted to extrapolate some pragmatic issues and past experiences at JPL in ground telerobot systems and in flight telerobot mechanisms, and has condensed these experiences in a systematic fashion. These design problems will continue to challenge designers, system architects, and managers until the telerobot technology further matures.

ACKNOWLEDGMENTS

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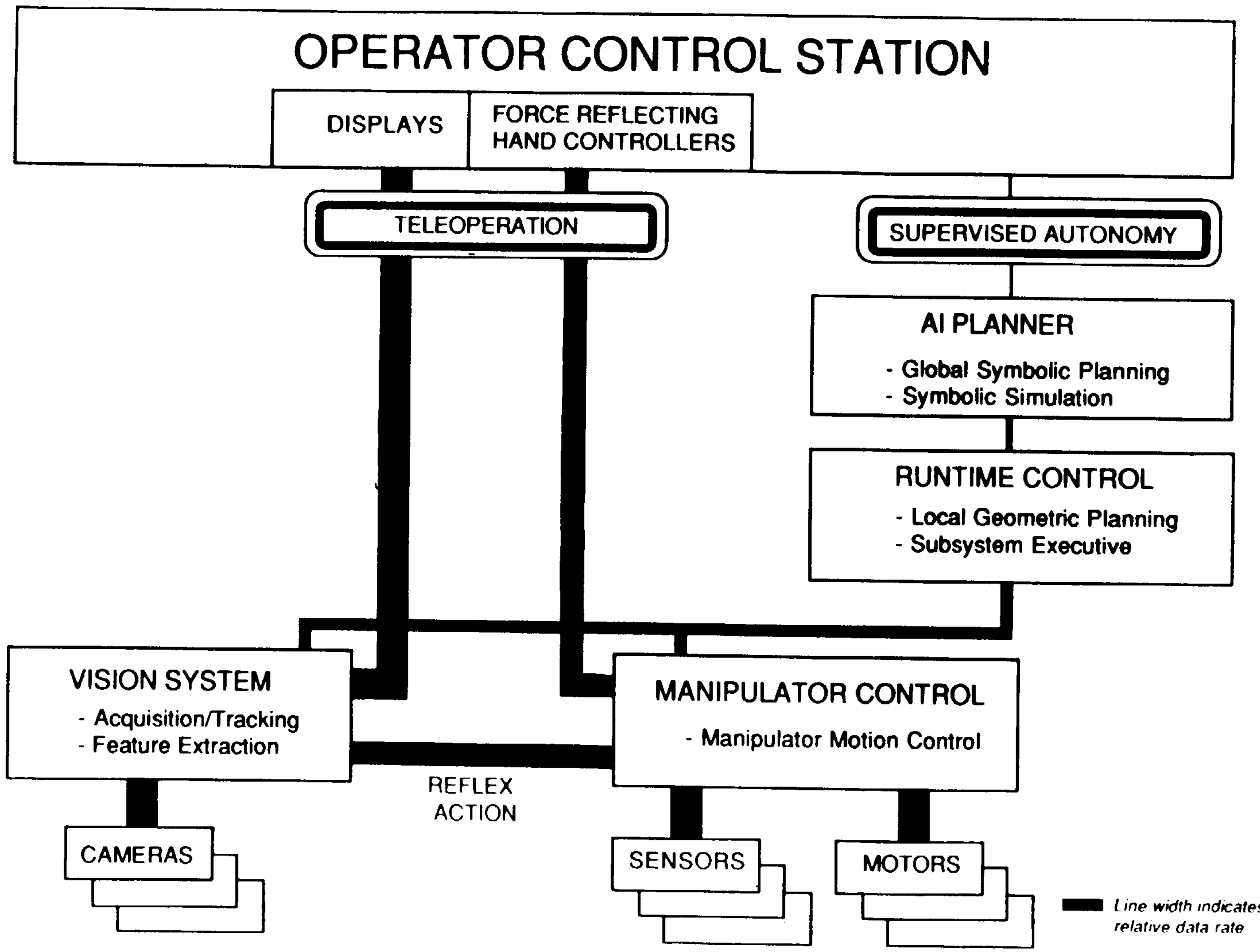

Figure 1. The JPL Telerobot Demonstration System Architecture.

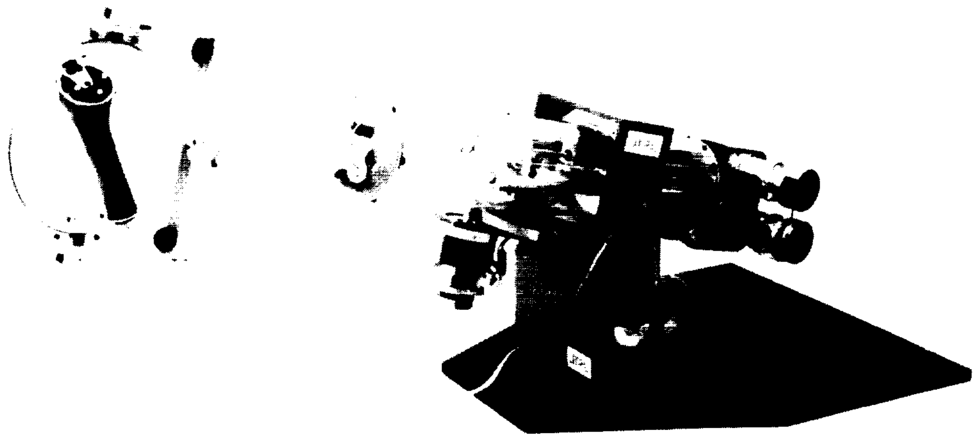

Figure 2. The JPL Force Reflecting Hand Controller (ground version).

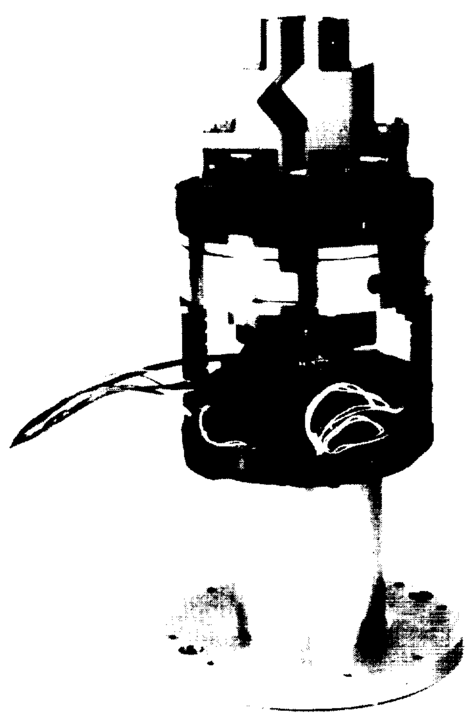

Figure 3. The Smart End Effector (GSEE for GSFC).

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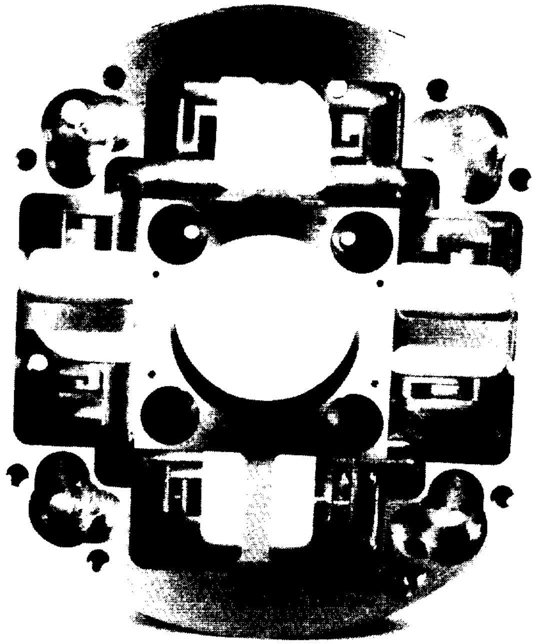


Figure 4. Force-torque sensor (ground version).

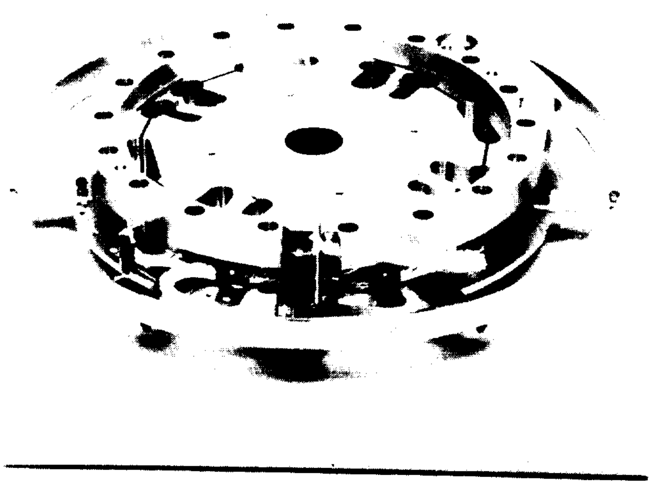
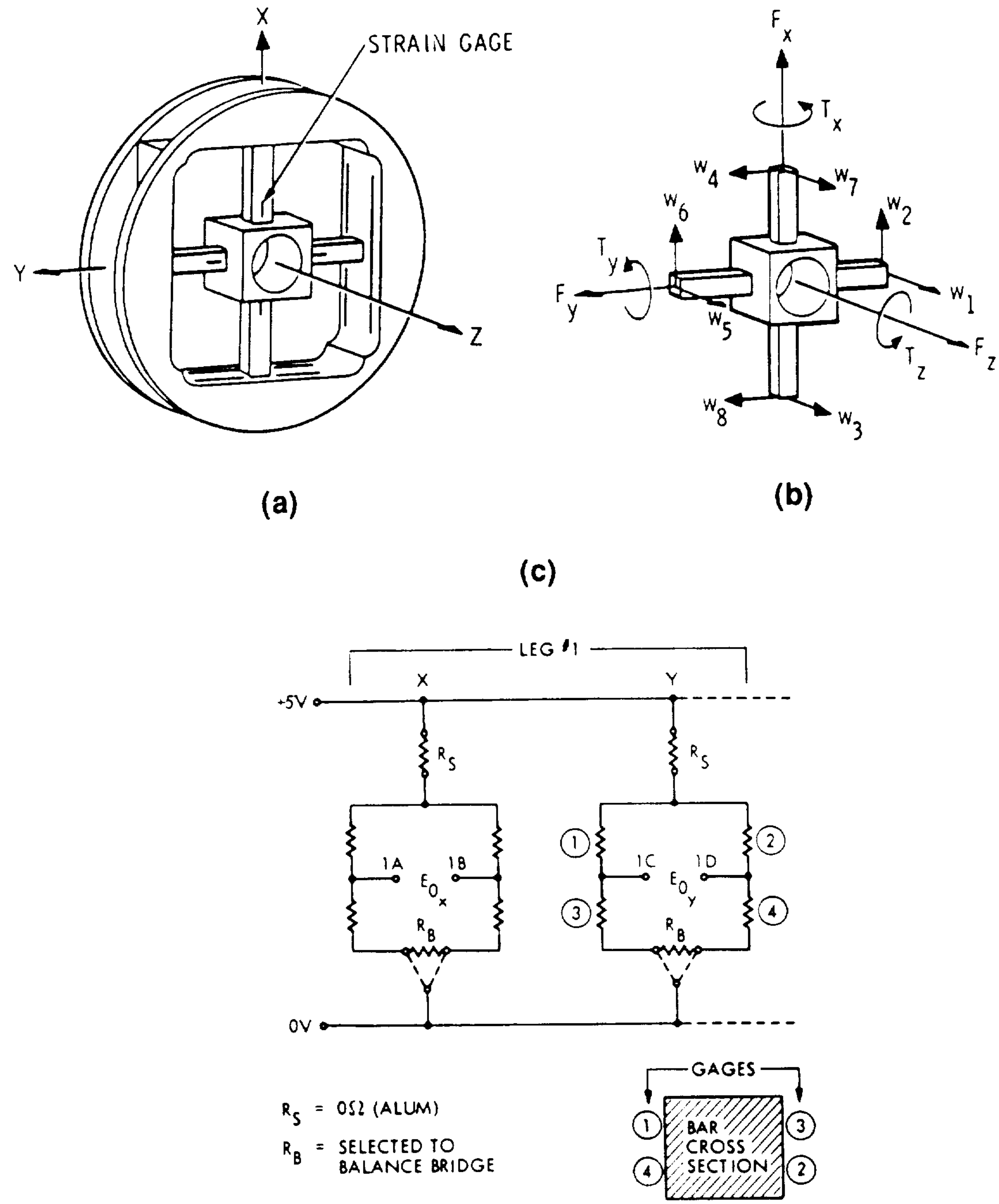


Figure 5. Force-torque sensor (flight version).



(a) Placement of strain gauges on the cross beams.
(b) Resolution of 6-DOF forces/torques into strain gauge strain components.
(c) Circuit diagram for wiring strain gauges.

Figure 6. Schematics of the force-torque sensor.

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Shown in figure: (a) a generic Operator Control Station with two FRHCs, (b) two manipulating robot arms with grippers, instrumented with force-torque sensors, (c) one vision robot arm, and (d) the task: grappling and working with a mock-up satellite.

Figure 7. The JPL/NASA Telerobot Demonstration System.